NASA Contractor Report 201140

An Engineering Model for the Simulation of Small-Scale Thermospheric Density Variations for Orbital Inclinations Greater Than 40 Degrees

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U.S. Government Agencies and U.S.
Government Agency Contractors Only

Contract NAS8–38333
Prepared for Marshall Space Flight Center

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EXECUTIVE SUMMARY

This report describes the development of an engineering model that simulates small-scale density variations in the thermosphere, and provides engineers with a set of instructions enabling them to implement the model in their existing orbital propagation models. The model is provided as a callable subroutine that can be easily used in conjunction with the MET model, and is simplistic enough to contain the essential elements of the variations without overburdening computational resources. The model FORTRAN code is included at the end of this report.

The model is derived from the spectral analysis of thermospheric neutral density data obtained from the Neutral Atmosphere Temperature Experiment (NATE) on the Atmospheric Explorer - C satellite between December 1974 and December 1978. During this time, the 68.1° inclination orbits were approximately circular between 220 and 400 km altitude. Solar activity was low to moderate during this period.

Total densities for contiguous strings of 15 second density data values were spectrally analyzed, and Fast Fourier Transform periodograms were computed for each string. The periodograms were binned according to latitude and the geomagnetic activity index a_p, and then average periodograms were computed for each bin. Finally, stochastic (autoregression) models were fit to each of the average periodograms. Two latitude bins and two a_p bins were employed.

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INTRODUCTION

The Marshall Engineering Thermosphere (MET) model (Hickey, 1988a, b), which defines the total mass density at thermospheric altitudes, has been specified for use in engineering analyses related to space vehicle development programs within NASA. The model is essentially that of Jacchia (1970, 1971), and provides the neutral thermospheric density as a function of altitude, day of the year, time of day, daily $F_{10.7}$, the 162-day mean $F_{10.7}$, and the three-hourly geomagnetic index, a_p.

Until recently, the shortest time scale variations within the MET model were those occurring every three hours as a result of the a_p variations. Now, however, variations with much shorter time scales can be included in the MET model for orbital inclinations less than 40^o using a simulator of atmospheric gravity waves developed by Hickey (1993). This simulator was based on the spectral analysis of mass spectrometer data obtained from the Atmospheric Explorer E (AE-E) satellite, as described in Hickey (1993, 1994). Since these were in situ data measurements, the wave structure is that experienced by the satellite. Because AE-E was a low inclination satellite (19.7 degrees), latitudinal variations of wave activity, which were not expected to be significant over this latitude range, were not modeled. At that time Space Station Freedom was being designed for a low inclination orbit (less than 30 degrees), for which the low latitude wave simulator would have been well suited.

However, with the entrance of the Russians into the program, the orbital inclination for THE International Space Station was changed to 51.6 degrees, making the low inclination wave simulator unsuitable for two reasons. One, most of the thermospheric wave activity originates at high latitudes; therefore, the International Space Station would be much closer to the wave sources during certain portions of its orbit; and, two, most large scale thermospheric waves propagate equatorwards from their high-latitude source regions with their phase fronts aligned almost parallel with lines of constant latitude. Therefore, a satellite in a high inclination orbit would experience the waves over the entire orbit differently than a satellite in a low inclination orbit. The wavelengths experienced by two satellites at different orbital inclinations would be different.

The model based on the low-inclination AE-E data overestimates the true wavelengths, i.e., the wavelengths measured in a North-South direction in the Earth reference frame. Therefore, in that model, spectral energy for a given wavelength was assigned to a much larger (the apparent) wavelength. The net effect of this was to shift the true spectrum to longer wavelengths by a constant factor. The model, therefore, would under predict the true spectral energy content of waves for a high inclination orbit because the spectral energy increases towards the larger scale sizes. This difference between "apparent spectra" and "true spectra" was briefly discussed in Hickey (1994, p.24).

Therefore, we expect that latitudinal variations in wave activity will be significant for the new, high inclination Space Station orbit. Consequently, there has arisen a need to accurately characterize the waves for both low and high inclination orbits. This characterization is the subject of this report. The final product is a callable subroutine that can be easily used in conjunction with the MET model, or with any empirical thermospheric model. As in Hickey (1993, 1994), the simulator is simplistic enough to contain the essential elements of the variations without overburdening computational resources.

The first half of this report is devoted to describing the data analysis procedures and the model development, and providing some sample output from the model. The second half of the report is devoted to describing how the model is implemented for engineering applications, with a complete description of all of the model inputs. Limitations in the use of the model are also provided here, and the complete FORTRAN program listing is provided at the end of the report.

PART I: MODEL DEVELOPMENT

I.1 DATA ANALYSIS

I.1.1 THE DATA

In this study we use mass spectrometer data obtained from the Atmospheric Explorer C (AE-C) satellite. AE-C was launched on 13 December 1973 with an orbital inclination of 68.1 degrees (Burgess and Torr, 1987). Its initial orbital period, apogee and perigee were 132.4 minutes, 4300 km and 154 km, respectively. The apogee and perigee were changed several times during the mission and the orbit was approximately circular about one year after launch.

The AE-C data used here were obtained with the Neutral Atmosphere Temperature Experiment (NATE) (Spencer et al., 1973). The analyzed data were provided on magnetic tape by the National Space Science Data Center (NSSDC) at NASA's Goddard Space Flight Center in Unified Abstract files with data at every fifteen seconds of orbit. These data consisted of the usual "navigation" data (date, time, altitude, latitude and longitude), as well as temperature and specie number densities, N_2, total oxygen (here we assumed this to be all atomic, a reasonable assumption in the middle thermosphere and above), Ar and He. The original data, with a one-second time resolution, was averaged over a fifteen-second time interval and stored in the Unified Abstract files at NSSDC. For these Unified Abstract data instrumental noise should be largely smoothed-out.

Additional data employed throughout this analysis consisted of daily values of $F_{10.7}$ and 3-hourly values of the planetary magnetic index (a_p), which form part of the Space Station Data Base at MSFC.

I.1.2 METHOD OF ANALYSIS

First, total mass densities were computed by summing the individual species number densities and were then compared with the MET model as a means of discriminating any bad data from good. (Note that we could have employed the MSIS model (Hedin, 1987) instead of the MET model for this purpose, with the result that a different amount of data would have been rejected). In Hickey (1993, 1994) a factor of three was used, so that there, AE-E density (ρ_{AE}) was considered good if $3\rho_{MET} \geq \rho_{AE} \geq 0.3\rho_{MET}$. Here, for the

AE-C data, we employ the same factor. It is a somewhat arbitrary factor, but does serve the purpose of rejecting the most probable bad data. A factor that is much smaller than three will assign too much certainty to the MET model, reject potentially good data, and further reduce the amount of useful data available for analysis. Of almost 147,000 NATE density values, almost 12,000 (~ 8%) were rejected after comparison with the MET model densities.

Next, data strings comprising contiguous data and having a prescribed minimum number of data points were constructed and binned according to their respective latitudes and a_p values (see discussion on bins). Here, unlike the previous AE-E analysis, the minimum acceptable length of a data string was 76 points, corresponding to a time span of about 19 minutes and a horizontal extent of about 8900 km (assuming an orbital speed of 7.8 km/sec). Thus, the minimum acceptable length of a data string was slightly greater than about one-fifth of an orbit.

The altitude variation in each string was then calculated. If the orbit was too eccentric, and this altitude variation exceeded 60 km (over at most a fifth of an orbit), the data string was discarded. This was done to minimize errors associated with interpolating densities to a common altitude (see next paragraph). These errors can be attributed to a), the inappropriate use of a constant local scale-height over large vertical distances, and b), neglecting the vertical phase variations of any small-scale density structures. These errors would not be expected to be important at higher thermospheric altitudes because the atmosphere is approximately isothermal there (so that scale-heights are constant), and because only the larger scale waves, with small vertical phase variations, survive the molecular and ion-drag dissipation there.

For each data string the mean altitude was calculated, and the number densities for only atomic oxygen and molecular nitrogen, the most important species between 250 and 450 km altitude, were interpolated to that mean altitude using the diffusion equation appropriate for an isothermal atmosphere (see Equation 1 of Hickey, 1993 and 1994) with the relevant values of atomic and molecular weights for the individual species. The temperature was also required for the determination of the scale-height. Here, unlike the previous AE-E analysis, we employed temperatures output from the MET model to provide us with an average temperature over each data string. Temperatures provided by the AE-C NATE instrument were not used because they were only available for about the first half of the AE-C mission. Although MET model temperatures are not considered to be accurate, they are probably good to within about 25% (though they are sometimes much better than this). Because we interpolated densities over altitudes of only about 30 km, or half a scale-height, interpolation errors in total density associated with errors in temperatures are only expected to be about half of the error in temperature, or about 12 %. Because there are no wave variations in the MET model, these temperature-related interpolation errors will all be of the same sign for each data string, and so will just offset the mean by no more than 12%. After November 1974 AE-C orbits were approximately circular so that the interpolation distances were very small and errors associated with using MET model temperatures were then negligible. The total mass density at the mean altitude was then calculated for every data point within the string by summing over the two species.

For each data string the mean density (ρ_{mean}) was calculated, and then the relative fluctuation amplitude (A) was calculated according to

$$A = (\rho - \rho_{mean}) / \rho_{mean} \qquad (1)$$

Note that A contains all frequency components including large-scale trends.

In the previous AE-E analysis the data were filtered before spectral analysis to remove the large-scale trends. The filtering included fitting a third degree polynomial to the data, and then subtracting this polynomial trend, followed by smoothing the data using a moving average filter. Such filtering can introduce biases in the data and affect the power spectrum, and although such effects were not thoroughly assessed in the previous AE-E analysis they were generally observed to be small. Here, we do not perform this type of data filtering, but instead use the fitting procedure of the autoregressive model to remove these very large scale trends, as discussed next.

The FFT periodogram of the data was calculated for each individual string of amplitudes after pre-whitening (i.e., differencing) and application of a Hanning Filter to reduce spectral leakage. Within each latitude and a_p bin the individual spectra were summed, and finally an average FFT spectrum for each bin was calculated.

As with the AE-E analysis, the ultimate goal of the present study was to find a parsimonious autoregressive (AR) model having similar attributes to the AE-C data. Examination of the resulting FFT periodograms, to be discussed in the next section, showed that a second-order AR model was required to achieve a good fit to these spectra. The relevant equations for the AR model are provided in Hickey (1993, 1994) and will not be repeated here (the interested reader is referred to Box and Jenkins (1976), for a good explanation of autoregression models). The only exception to this concerns an error in equation 7 of Hickey (1994) relating the variance of a process (σ^2) to the estimated white noise variance (σ_a^2) and the correlation coefficients (φ_1 and φ_2). The corrected equation is:

$$\sigma^2 = \left(\frac{1-\varphi_2}{1+\varphi_2}\right)\frac{\sigma_a^{\ 2}}{\left\{(1-\varphi_2)^2-\varphi_1^{\ 2}\right\}} \tag{2}$$

Previously with the AE-E analysis, the large-scale trends were removed from the data before calculating the FFT periodograms. This was to ensure that only the gravity waves were modeled. The autoregressive models that were used to fit these periodograms were devised so that the power spectral density would asymptote to a constant at long wavelengths (or periods). It was noted there (Hickey, 1993, 1994) that this "roll-off" was required to ensure that the total energy content of all variations (the wavenumber or frequency integrated power) remains finite. It was also noted that because the MET model dominates the power spectral density at the largest scale sizes, the actual value of the asymptote was not too important. These findings have been utilized to advantage in the present study in the following way.

First, the large-scale trends in the AE-C data were not removed before the FFT periodograms were calculated (the means were always removed, however). This meant that much shorter strings of data could be analyzed here compared to the previous AE-E analysis because there thirty-five data points were lost by applying the moving-average filter. Thus, although original data strings comprised one-hundred and twenty-eight points in the AE-E analysis, only ninety-two remained for spectral analysis (compared with seventy-six used here). Second, in this study the large-scale trends do not have to be (and were not) included in the autoregressive fit to the spectra. The asymptote, discussed in the previous paragraph, was chosen so that the large-scale trends could not contribute to the AR model. The power then "rolled off" at large scale sizes, instead of following the power curves that were most certainly due to these large-scale ("mean" atmosphere) trends. We again note that the power due to these large-scale trends is essentially provided by the MET model.

I.2 RESULTS

Experimentation with binning, and experience gained in the previous AE-E analysis, suggested that no more than two a_p bins should be employed in this AE-C analysis. Part of the reason for this lies in the common belief that the a_p index is not a suitable indicator of wave activity, as discussed in Hickey (1994, p.25). The nature of the data and analysis methods placed a very rigid constraint on the possible number of latitude bins. Clearly, data strings had to be long enough to include the larger-scale gravity waves. With the AE-C orbital inclination of about 68° only two latitude bins could be included. One, the low-latitude bin, lay between ± 40°, while the other, the high-latitude bin, lay beyond ± 40° (and, of course, less than 68.1°). If we had chosen to employ three latitude bins, then the data strings would have been much shorter, and the larger-scale waves would not have been spectrally characterized. With two bins for both latitude and a_p the data were sorted into a total of four bins. In all, approximately 20,000 NATE density values were spectrally analyzed.

Two typical strings of O number density data, both before and after reduction to a constant altitude, are shown in Figure 1a and 1b. For this example, the values of latitude and a_p are not relevant, and the time origin is set at the start of the data string. Large undulations in the number density are apparent.

The average FFT power spectral density for each latitude and a_p bin is shown in Figure 2. These average FFT power spectral density functions were calculated by averaging many such individual spectra at each frequency. The individual power spectral density functions were obtained using a multivariate complex Fourier transform routine (Singleton, 1969), and then normalizing the power by multiplying by the sampling time interval (15 s). Data were prewhitened and a Hanning filter was also applied to the individual spectra to reduce the leakage of energy from the low to the high frequencies. Also shown in Figure 2 are the 90% and 99% confidence intervals calculated by assuming that the power at each frequency follows a chi-squared distribution with 2N degrees of freedom, where N is the number of spectra involved in the averaging, and the factor of 2 appears because every complex number has associated with it 2 degrees of freedom, one for each of its real and imaginary parts (chi-squared distribution tables can be found in Selby's CRC Tables). The values of χ^2 for the various mean spectra and their corresponding confidence intervals are given for three different percentiles in Table 1.

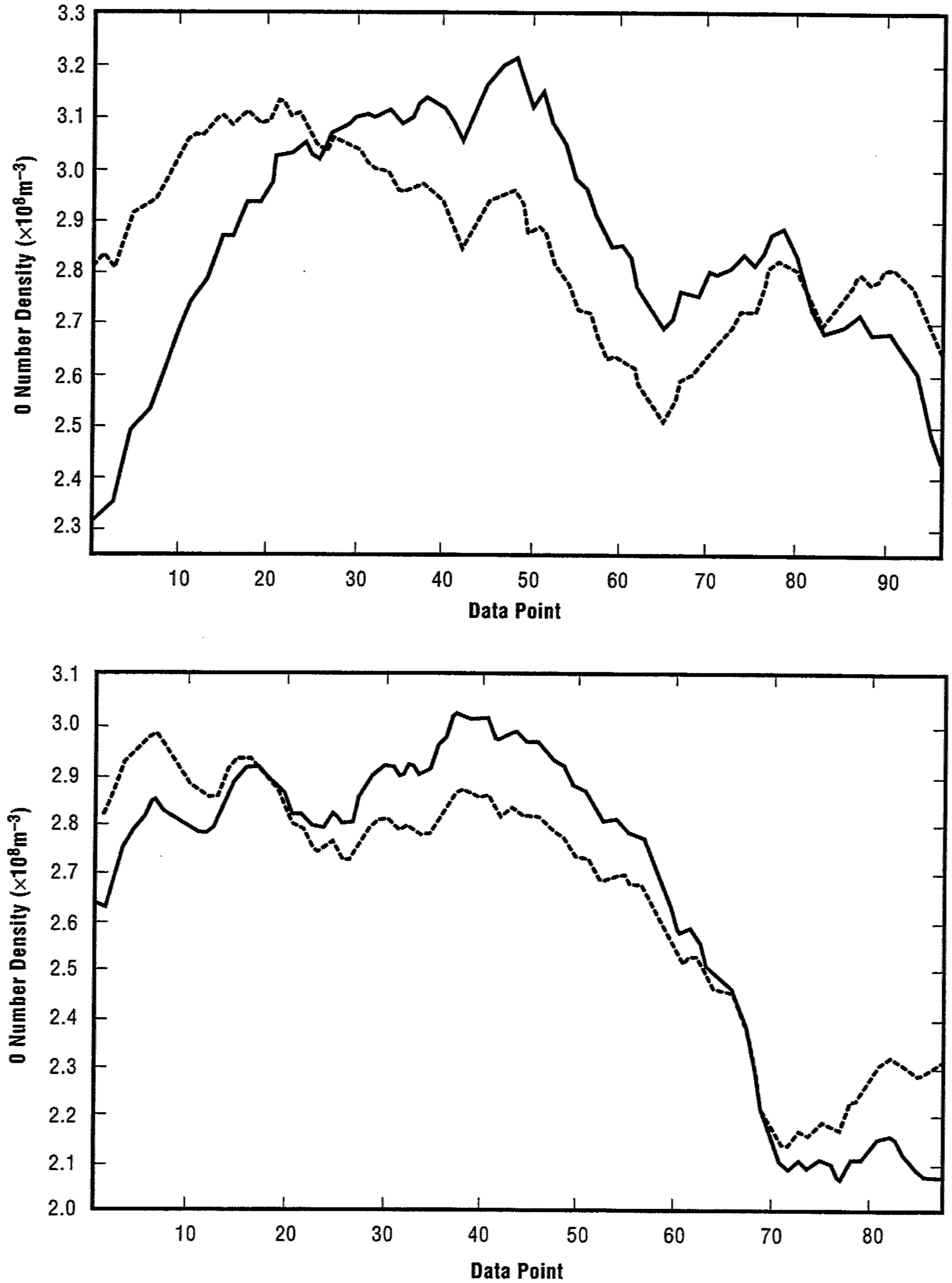

Figure 1. Two typical strings of oxygen number density data both before (——) and after (------) reduction to a constant altitude.

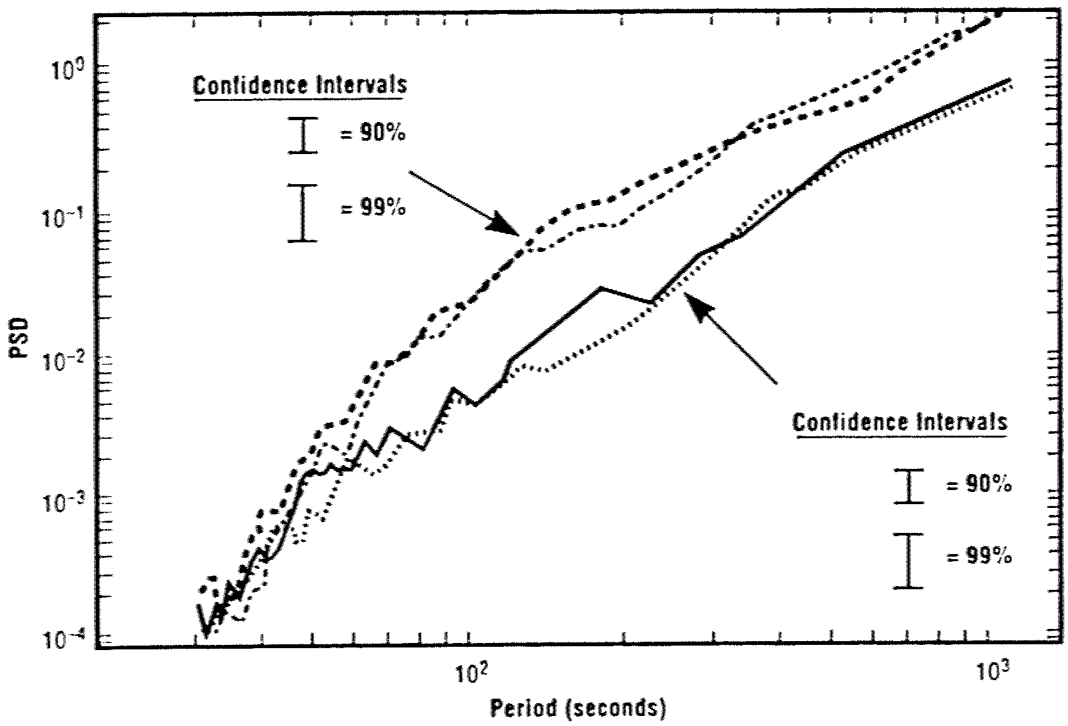

Figure 2. Power spectral density for each latitude and a_p bin: low latitude, low a_p (solid line); low latitude, high a_p (dotted line); high latitude, low a_p (dashed-dotted line); high latitude, high a_p (dashed line). The 90% and 99% confidence intervals calculated from a chi-squared distribution are also shown.

Table 1. Number of series averaged (N), number of degrees of freedom (μ), and the corresponding values of χ^2 with the confidence interval (CI) for the 90th, 95th and 99th percentiles.

N	μ	$\chi^2_{0.90}(\mu)$	CI	$\chi^2_{0.95}(\mu)$	CI	$\chi^2_{0.99}(\mu)$	CI
29	58	72.16	0.80	76.78	0.76	85.96	0.67
28	56	69.92	0.80	74.47	0.75	83.53	0.67
92	184	209.0	0.88	216.7	0.85	231.5	0.79
107	214	240.9	0.89	249.1	0.86	265.0	0.81

It is clear that the variations are more energetic at high latitudes compared to low latitudes, as expected. Also, at high latitudes, the variations occurring with periods smaller than about 330 seconds (wavelengths smaller than about 2600 km) are more energetic for high a_p than for low a_p. The reverse is true at larger scale sizes. At low latitudes, differences are not as clear, although the smaller-scale variations appear to be less energetic for high a_p. The spectra are generally different at about the 90% level assuming a chi-squared distribution for power at each frequency. Exceptions to this occur for the high-latitude spectra near a period of 200 seconds, where the low and high a_p spectra are different at the 99% level, and at periods greater than about 200 seconds, where the low and high a_p spectra are not statistically different.

The range in power spectral density is greater at high latitudes. Because the range is large for all latitudes, about four orders of magnitude, experience with fitting autoregression parameters to spectra suggests that a second-order autoregression process is required to model these FFT spectra. The autoregression parameters that gave the overall "best fit" to the mean spectra are provided in Table 2. These parameters ensured that the power spectral density asymptotes to a constant at long periods (on the log-log plots). Such a power "roll-off" is required to ensure that the total energy content of all variations (the frequency integrated power) remains finite. As explained previously, the exact value of this asymptote is not too important.

Table 2. Number of series, autoregression parameters and estimated white noise variance for each latitude and a_p bin.

Lat	a_p	# Series	φ_1	φ_2	σ_a^2 (x10^{-4})	σ^2 (x10^{-3})
1	1	29	1.1792	-0.24832	1.9195	1.8990
1	2	28	1.2764	-0.33955	1.3706	1.6823
2	1	92	1.4367	-0.51164	4.3796	6.1340
2	2	107	1.3461	-0.42737	5.9512	6.5834

The mean power spectral densities and their autoregression lines of best fit for low latitudes are shown in Figure 3. Figures 3a and 3b show the results for low and high geomagnetic activity, respectively. The corresponding results for high latitudes are shown in Figure 4. The autoregression lines have been deliberately chosen to give a better fit at periods longer than about 100 seconds (wavelengths longer than about 780 km) than at the shorter periods. This is primarily because the Space Station is apparently more affected by these larger scale variations. Note the power "roll-off" at long periods, as mentioned before.

A wave simulation FORTRAN subroutine (WAVES2; this subroutine is included in the Appendix) was written that required the latitude and a_p bins, as well as a seed for the random number generator, as input. (The random number generator subroutines employed, RAN1 and GAUSSD, were selected for portability and reliability (see Press et al., 1986).

Example output from the wave generation routine is shown in Figures 5a, 6a, 7a and 8a, while their power spectral density is shown in Figures 5b, 6b, 7b and 8b. The same initial random number seed was used in all of these examples The example shown in Figure 5a is applicable to the lowest latitude and a_p bins. One notices the quasi-periodic nature of the generated time series, and that the wave amplitudes never exceed about 10%. The power spectral density of the simulated waves (Figure 7b) resembles that of the original data (Figure 3a) although the latter, being an average, has less statistical variation associated with it. Similar results are obtained for the lowest latitude and high a_p bin (Figures 6a and 6b). Again, amplitudes rarely exceed about 10%. These low latitude results are essentially in agreement with the results obtained from the previous analysis of the low latitude AE-E data presented by Hickey (1994). The results for the high latitudes,

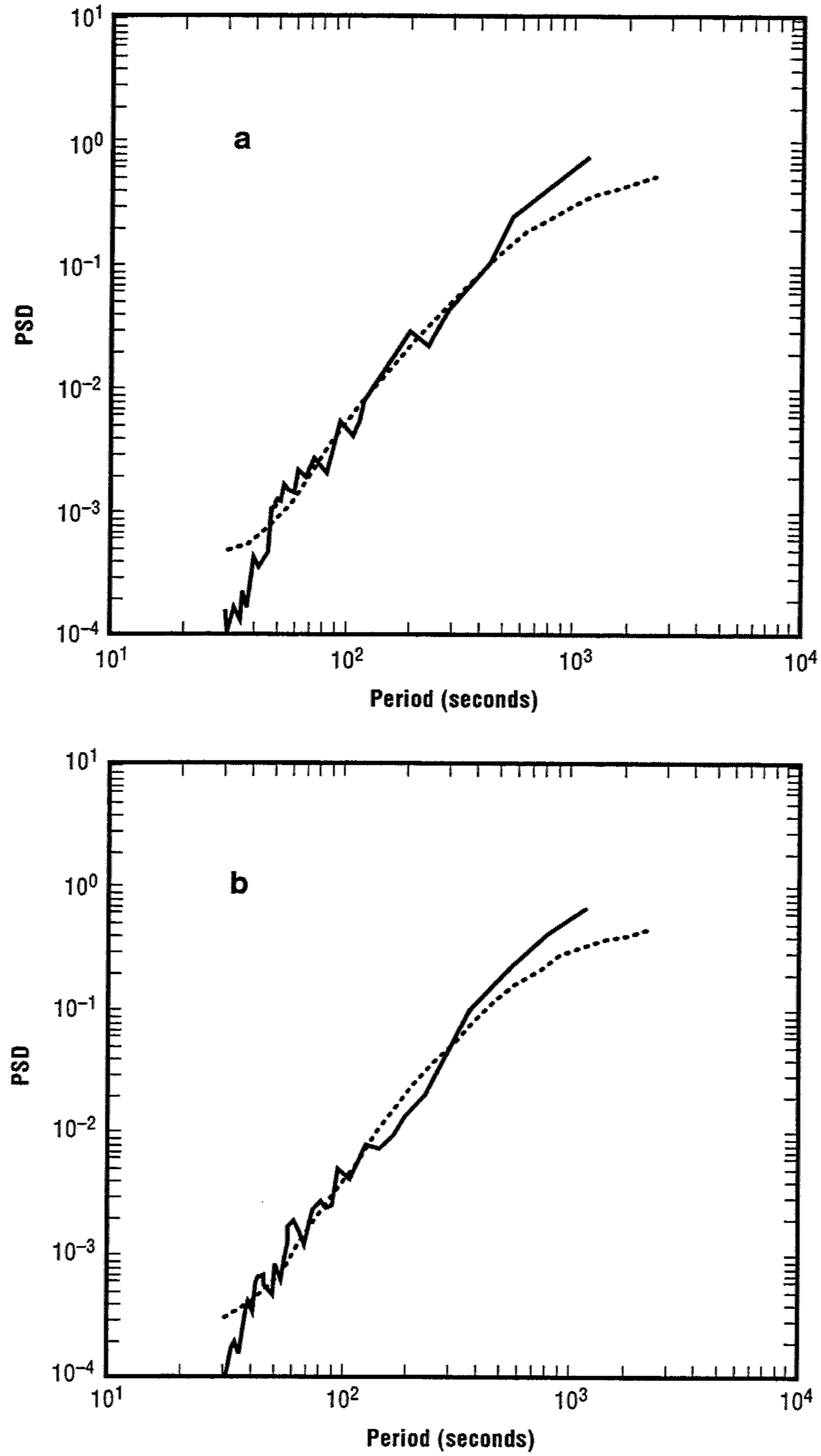

Figure 3. Power spectral density (——) and the Maximum Entropy spectrum derived from the "best-fit" autoregression parameters (------) for low latitudes and for (a) low, and (b) high a_p bins.

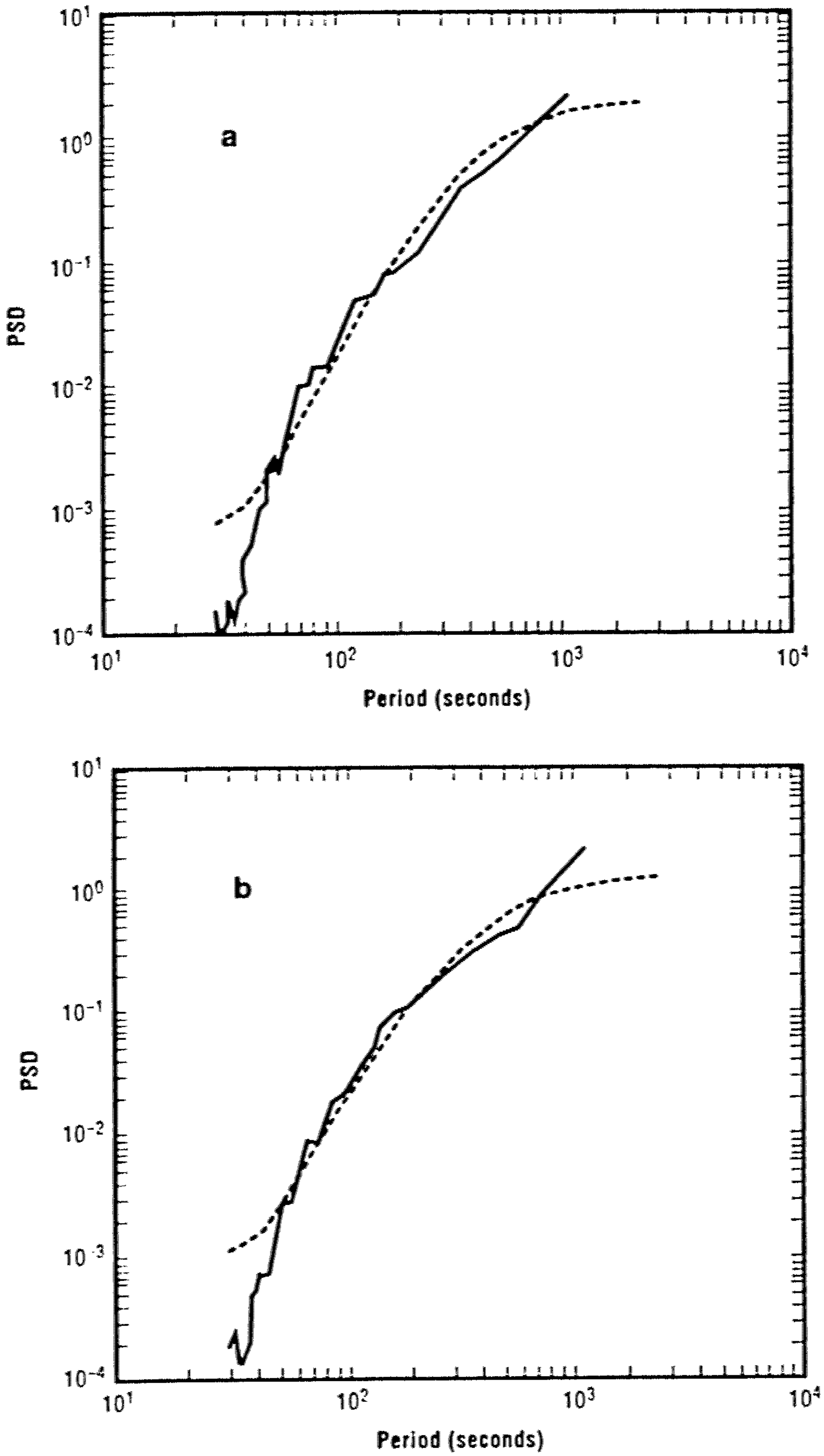

Figure 4. Power spectral density (——) and the Maximum Entropy spectrum derived from the "best-fit" autoregression parameters (------) for high latitudes and for (a) low, and (b) high a_p bins.

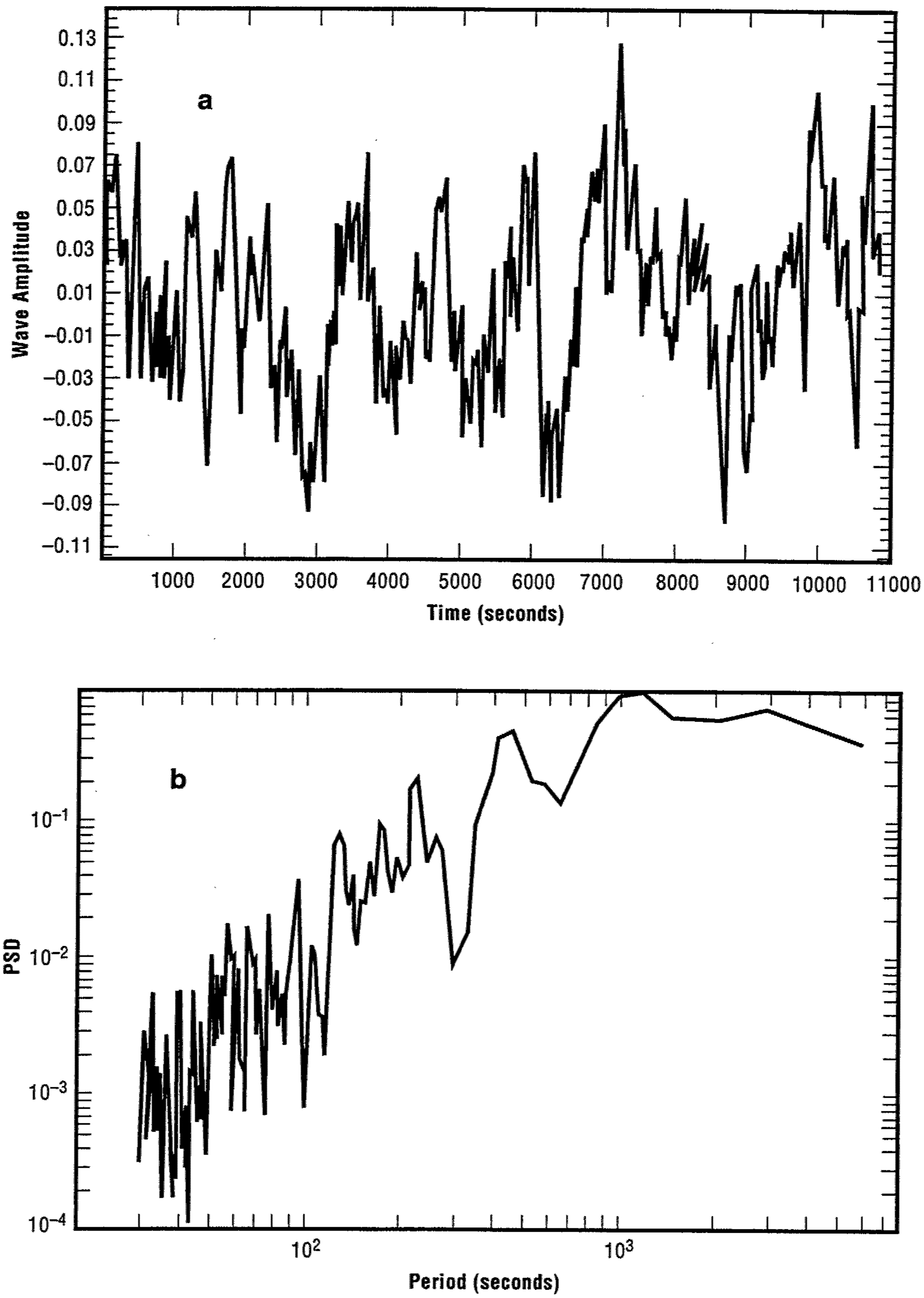

Figure 5. Wave amplitudes (a) and their power spectral density (b) for the low latitude, low a_p bin.

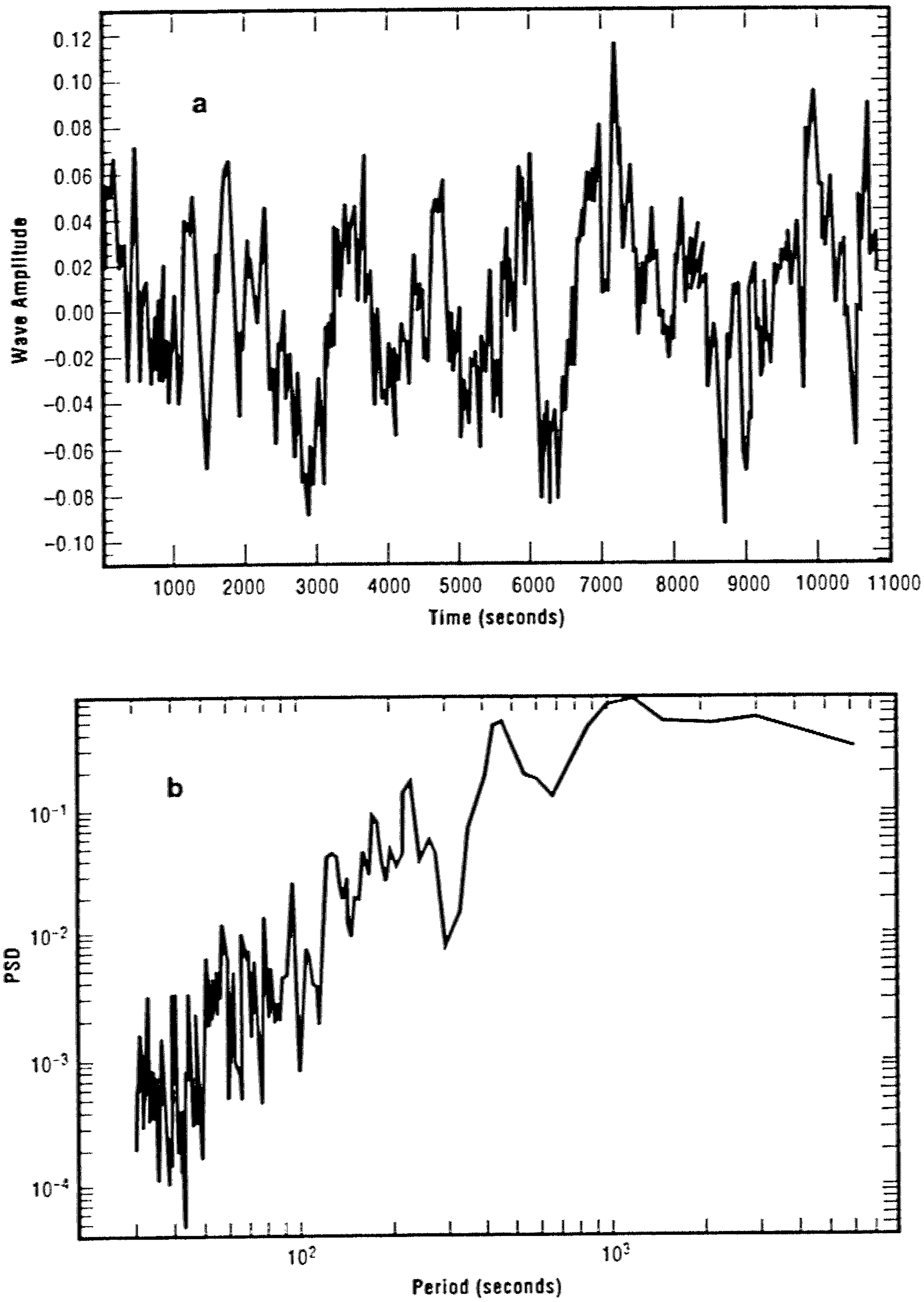

Figure 6. Wave amplitudes (a) and their power spectral density (b) for the low latitude, high a_p bin.

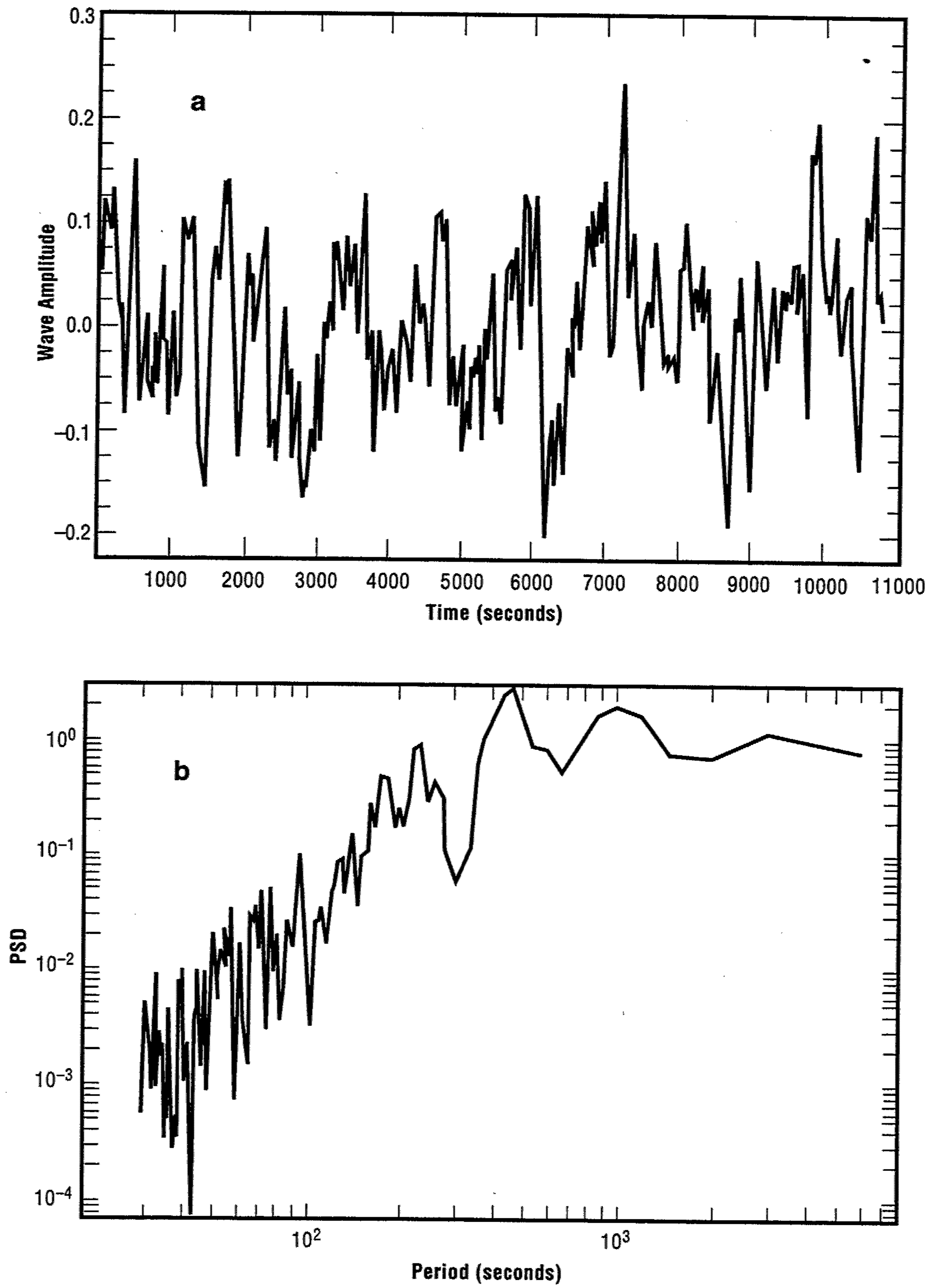

Figure 7. Wave amplitudes (a) and their power spectral density (b) for the high latitude, low a_p bin.

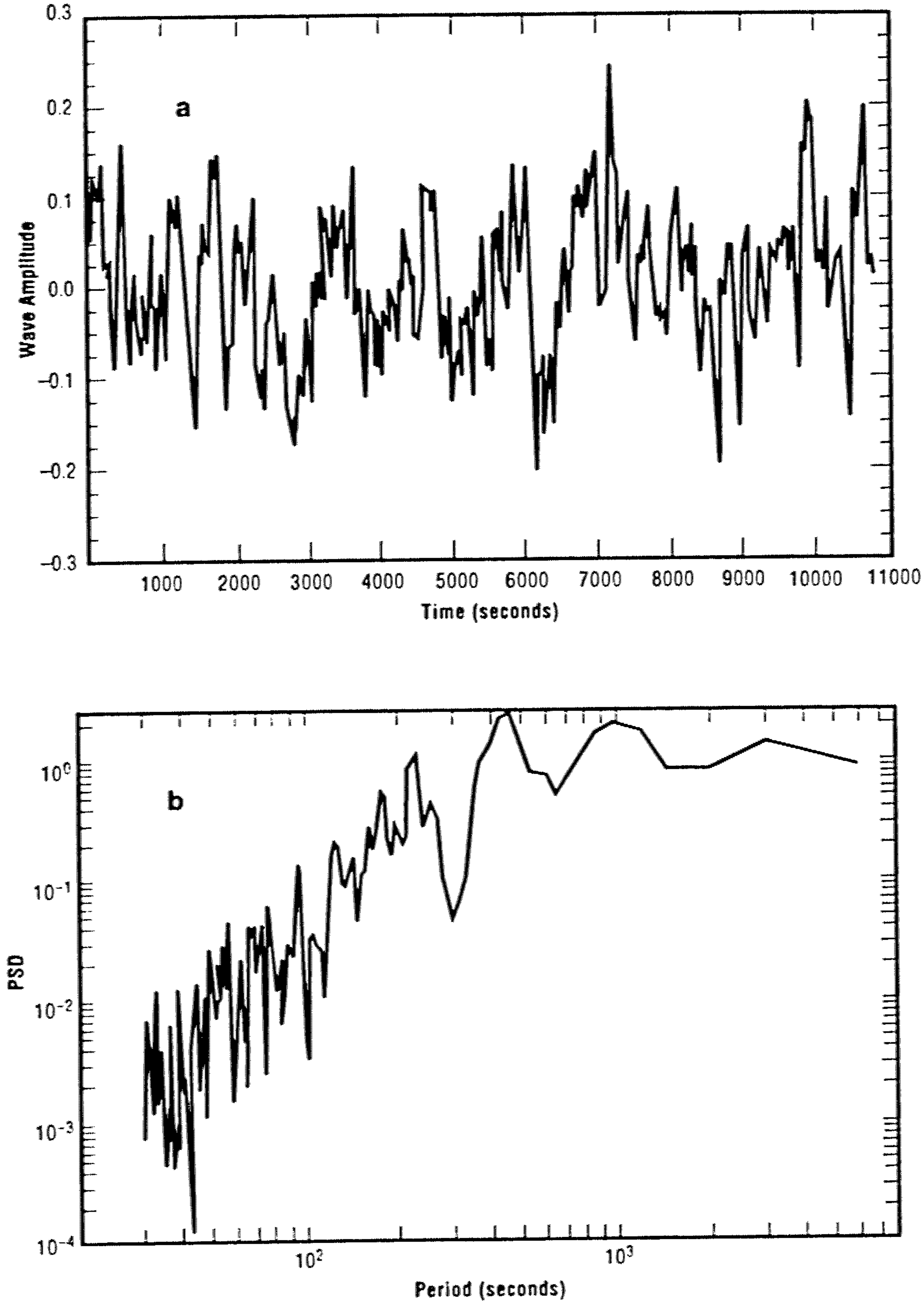

Figure 8. Wave amplitudes (a) and their power spectral density (b) for the high latitude, high a_p bin.

shown in Figures 7 and 8, are strikingly different. Amplitudes exceeding 10% are quite common, and occasionally reach about 20%.

The wave simulator was linked with the MET model, using two more FORTRAN subroutines (SETWAVE2 and GETWAVE2). The MET model can be run with the option of including the wave simulation, in which case the total density (ρ_{tot}) is given by

$$\rho_{tot} = \rho_{MET}(1+A) \tag{3}$$

where ρ_{MET} is the standard MET model density and A is the wave amplitude expressed as a decimal (i.e., 0.1 is equivalent to 10%).

An example of running the MET model first without and then with the wave simulation is shown in Figure 9. The density is calculated for 300 km altitude on 12 October, with $a_p = 0$, and the daily and 162-day mean $F_{10.7} = 100$ (these conditions correspond to the lowest bins for the wave simulator). Two simulations were performed when the waves were included, corresponding to conditions of low (Figure 9b) and high (Figure 9c) a_p, respectively. The variable PICKBINS was set to true, so that the a_p bin could be set manually and override the value of $a_p = 0$ (the same values of a_p were employed so that mean MET model densities were identical in the absence of waves). Note that had we selected PICKBINS to be false, then the correct bins would have been selected automatically using the MET model inputs. The density is shown at different local times around a polar orbit, with an arbitrary time (elapsed time) shown for the 90 minute orbit. Note that in this simulation the time steps were set at a constant one minute. The differences between the case of no waves (Figure 9a) versus the case with waves (Figures 9b and 9c) is clear. The density curves shown in Figures 9b and 9c resemble some of the original density data, as expected.

The final set of results of this analysis are presented in Figure 10. It was mentioned earlier that in order to conserve energy, the power spectral density is required to "roll-off" at long periods, and asymptote to a constant there. It was also stated that the actual value of this asymptote is not important. In order to demonstrate this, the MET model was run both with and without the wave simulation, and the FFT power spectral densities of the two time series were calculated. This was done for both the low and high a_p bins (Figures 10a and 10b, respectively). Clearly, the power decreases to insignificant levels at short periods without the inclusion of the simulated waves. Perhaps more importantly, however, is the fact that at long periods the simulated waves make only a very small contribution to the total power. Therefore, at these long periods most of the power comes from the MET model. This long period power results from the fact that the diurnal variation in the MET model is not a perfect sinusoid with a 24 hour period, but is a distorted sinusoid involving many harmonics of the diurnal period. These results justify our original claim that filtering of the data to remove the large-scale trends was not required in order to fit an autoregression process to the FFT data.

The wave model is stochastic, producing a Gaussian distribution of wave amplitudes. Extreme wave amplitudes will occasionally be realized for a large enough sample of amplitudes. A large sample of amplitudes can be generated with the simulator using a Monte Carlo approach, in which case the simulator is used to generate many sequences of wave amplitudes. Precisely how many simulations are required in the Monte Carlo approach is determined by the probability level required. More extreme amplitudes require more simulations in order to produce them. Typically, several hundred up to perhaps one or two thousand Monte Carlo simulations may be required to generate a 99th percentile value.

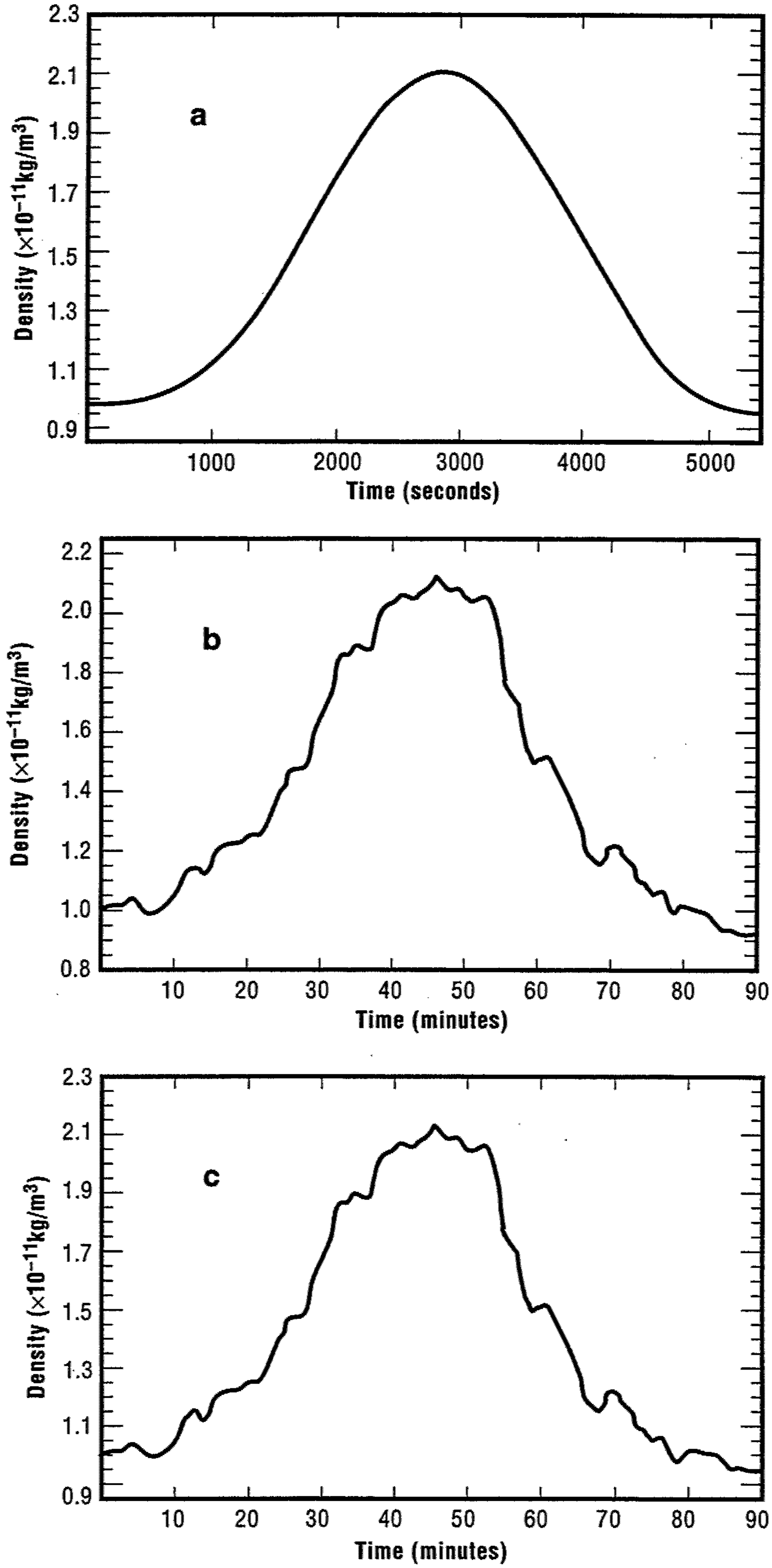

Figure 9. MET model densities for polar orbit (a) without waves, (b) with waves for the low a_p bin, and (c) with waves for the high a_p bin. See text for details.

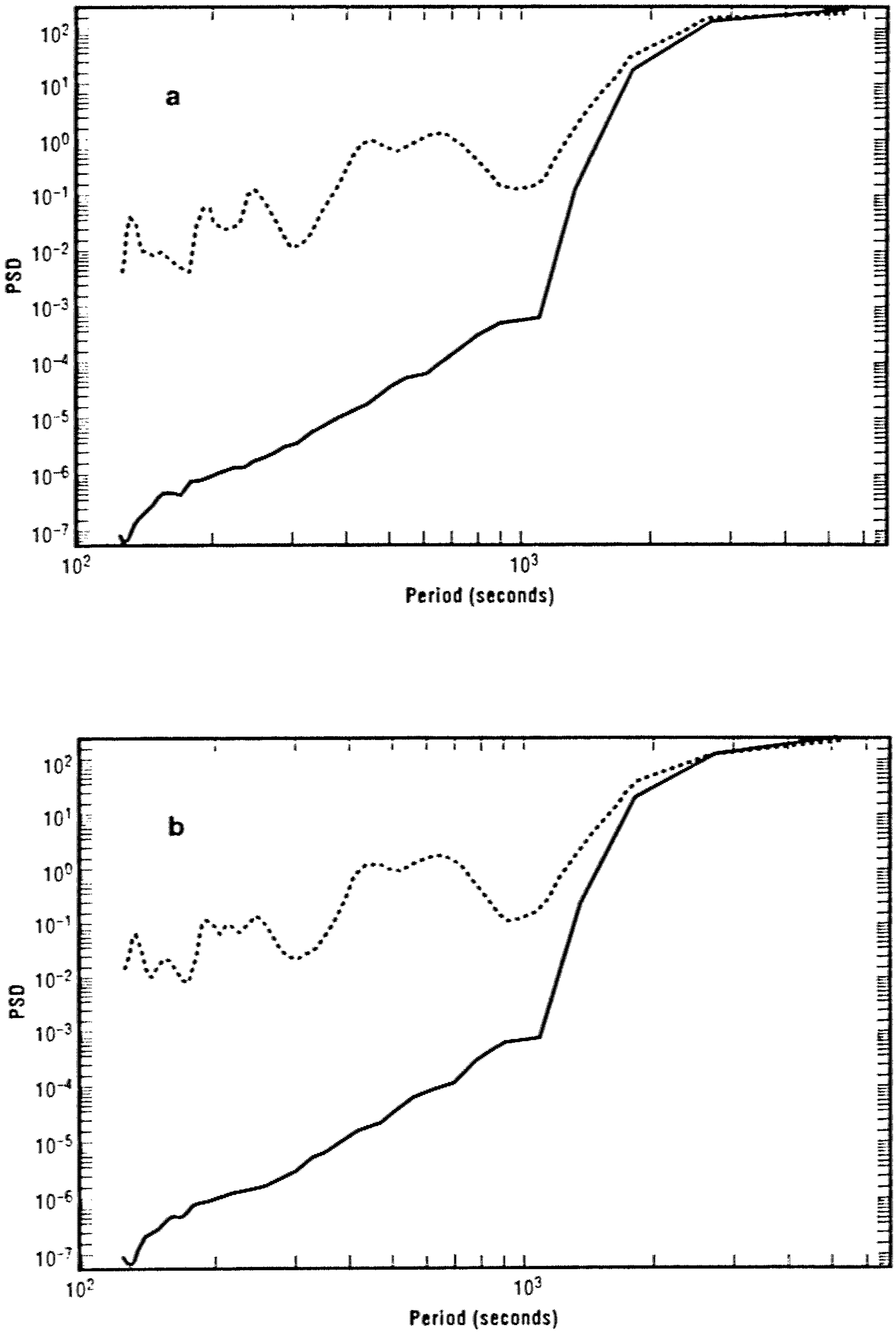

Figure 10. Power spectral density of MET model densities without (——) and with (------) wave simulation for both (a) low, and (b) high a_p bins.

PART II: APPLICATION GUIDELINES

II.1 MODEL LIMITATIONS

The model just described has, like most models, some limitations associated with it. These limitations are mostly associated with the limitations of the original data. Users of the model should be aware of these limitations so that they don't apply the model beyond the model's data base. These model limitations are now individually discussed.

Latitude Variations in the Data

The model is based on data obtained from a moderately high inclination satellite, with data being obtained at all latitudes between $\pm 68.1^{\circ}$. As with the previous AE-E analysis, the wave spectra reported in this document are still "apparent" spectra, although here they are probably closer to the true wave spectra than were the AE-E spectra. The high-latitude spectra may have some distortion or smearing in the frequency (or wavenumber) domain due to the fact that near the "top" of an orbit (i.e., near $\pm 68.1^{\circ}$) the satellite motion is predominantly along the wavefronts rather than across them (as it is at low latitudes). This effect is not expected to be in the low-latitude spectra.

Middle Thermosphere Data

The model is based mostly on middle thermosphere data obtained between about 200 and 450 km altitude. Based on the analysis of Hedin and Mayr (1987), it is unlikely that the wave amplitudes will change substantially with increasing altitude above 450 km, so that the model may be applied to greater altitudes (but not above about 500 km) without undue concern. However, the wave characteristics will undoubtedly change considerably with decreasing altitude below 200 km altitude, and it is strongly advised that the model not be used below an altitude of 200 km.

Throughout the analysis it was assumed that the spectral characteristics did not vary with altitude. The analysis of Hedin and Mayr (1987) suggests that this is a reasonable assumption, at least to first order. However, the altitude of AE-E was varied (increased) in response to increasing solar activity, except during the latter passive phase of the mission when the orbit decayed. Thus, both $F_{10.7}$ and altitude were simultaneously varying.

$F_{10.7}$ Variations

$F_{10.7}$ variations were not considered in this report. Their consideration would have degraded the statistics of the model by increasing the number of bins, thereby reducing the number of series for analysis in each bin.

a_p Variations

Our resulting wave spectra displayed a weak dependence on a_p. This result reconfirms our suspicions regarding the a_p index as a suitable indicator of wave activity, and also agrees with the findings of Chandra et al. (1979) and Forbes and Marcos (1973) that were discussed earlier in this report. The same result has also been found in more recently analyzed data (Forbes, 1993). It is clear that while the a_p index is a suitable indicator of enhanced global densities that occur on time scales of several hours in response to the energy deposition in the high latitude thermosphere, it cannot be used for variations occurring on time scales less than three hours (the resolution of the a_p index).

The a_p values employed were those occurring 6.7 hours prior to the time of interest, which is the same as that associated with the MET model. The wave model development also included the use of daily A_p values, which gave comparable results to those obtained using the a_p index. Differences were only marginal, and not considered to be significant enough to offset the added complexity of using a nonstandard index (A_p) in the wave model while also using the standard a_p index in the MET model.

The Auroral Electrojet (AE) index is probably more suited for the characterization of these short time variation phenomena (e.g., Chandra et al., 1979; Forbes and Marcos, 1973), but it is not currently baselined within the Space Station Program and was therefore not programmatically suitable for inclusion in the present analysis.

Diurnal and Seasonal Dependence of Wave Spectra

There are undoubtedly both diurnal and seasonal dependencies of the thermospheric wave spectra. However, the statistics would have been significantly degraded by the introduction of the additional binning required to study and characterize these variations. The dependence of the wave spectra on time of day and season is well established for the smaller scale waves of tropospheric origin propagating into the thermosphere, and is mainly due to the filtering action of the middle atmosphere winds on the waves (e.g., Cowling et al., 1971; Waldock and Jones, 1984). The source of the larger scale waves that are produced in the high latitude thermosphere will have a diurnal dependence, because most of the energy deposition within the auroral oval occurs in the evening sector around local midnight (e.g., Roble et al., 1979). This is confirmed by the many observations referenced by Hunsucker (1982). Also, geomagnetic activity has a seasonal dependence (Russell and McPherron, 1973; Cage and Zawalick, 1972), although a seasonal dependence in the large scale thermospheric gravity waves has been more difficult to observe.

Simulation Time

A complete simulation is based on a fixed (i.e., constant) value of a_p. Because a_p is a three-hour index, it is likely to change every three hours. Therefore, the simulator code is set to run a complete simulation for no more than three hours. This does not mean that orbital simulations are restricted to three hours, however. It simply necessitates that the set-up routines be called again, with or without new inputs, and a new three-hour wave simulation can continue from where the previous three-hour simulation stopped. Tmax cannot exceed three hours.

Time Interval

The original data was provided every fifteen seconds, so that no information was provided for variations occurring on time scales shorter than fifteen seconds. Therefore, the time step (Dt) cannot be set to values smaller than fifteen seconds. If it is, then it is automatically reset to fifteen, and a warning may be issued.

II.2 USER'S SOFTWARE IMPLEMENTATION GUIDE

This section describes how to use the wave simulation model. In this section we employ the following conventions: subroutines and common blocks are written using all uppercase letters, while only the first character of a variable name is written using uppercase letters. There are several subroutines employed in the model. Their names, order of execution and functions are provided in Table A1, while their input and corresponding output are provided in Table A2.

Table A1. Subroutines, order of execution and functions.

Subroutine Name	Execution Order & call type	Function
SETWAVE2	1 Single call	Performs routine setup. Requires user input for option to explicitly select a_p bin, the initial random number seed, and the option to suppress warning messages.
GETWAVE2	2 Multiple call	Handles bookkeeping for WAVES subroutine. Inputs through argument list. Calls WAVES2 subroutine.
WAVES2	3 Multiple call	Computes stochastic wave amplitude. Inputs through argument list. Calls GAUSSD subroutine.
GAUSSD	4 Multiple call	Computes array of Gaussian random numbers. Inputs through argument list. Calls RAN1 subroutine
RAN1	5 Multiple call	Computes a single uniform random deviate between 0 and 1. Inputs through argument list.

These subroutines have been designed to be used in conjunction with both the MET model and an orbit generator, although in principle they will work with any empirical thermospheric density model. The subroutine WAVES2 is called and controlled by the subroutine GETWAVE2. The input and output of WAVES2 are thoroughly described in the comments accompanying that subroutine, and will not need further explanation here. The subroutine GAUSSD and the function subprogram RAN1, that together generate an array of Gaussian distributed random numbers, need no further explanation here except that the seed must be a large odd integer. The references from which these portable and reliable codes were obtained is given in the comments section of each of their program codes.

Table A2. Subroutines and their input and output.

Subroutine Name	Input Parameters	Output Parameters
SETWAVE2	**Pickbins**: user input **$A_p$bin** (if Pickbins true): user input **Iseed0**: user input **Warnings**: user input	**Iseed0**: through argument list **$A_p$bin** and **Warnings**: all through COMMON /WAVE/
GETWAVE2	**Metden, latin, $a_p$in,** and **Iseed0**: all through argument list	**Totden**: through argument list
WAVES2	**$A_p$in, latin, Dt, Tmax, Iseed, Reset, Pickbins, $A_p$bin, Warnings**: all through argument list	**Wave**: through argument list
GAUSSD	N and **Iseed**: through argument list	**Noise**: through argument list
RAN1	**Idum** (seed): through argument list	**Ran1**: function subprogram value returned

Correct implementation of the set of subroutines will require some additional comments regarding the subroutines SETWAVE2 and GETWAVE2. These are now briefly described.

Subroutine SETWAVE2

The subroutine SETWAVE2 must be called initially to set some of the inputs. If the decisions made during execution of SETWAVE2 are adhered to for the entire simulation or sets of simulations, SETWAVE2 need not be called again. In this case Iseed0, Pickbins and Warnings, as well as $a_p$bin if Pickbins is true, will all remain unchanged. If, however, Pickbins or Warnings need to be changed, then SETWAVE2 will need to be recalled. In practice it is unlikely, for example, that any user would want to run a simulation first without suppressing warning statements and then later suppressing them. It would seem equally unlikely that during the course of a set of simulations any user would need to change from using a predetermined a_p value to using a predetermined a_p *bin* values.

Subroutine GETWAVE2

The subroutine GETWAVE2 needs to be called directly after the total neutral mass density, that has been calculated from the mean-state thermospheric model (e.g., MET), has been returned to the orbit generator program. GETWAVE2 must be called every time that a new density value has been returned from the mean-state density model.

The first input parameter in the argument list of GETWAVE2 is Metden, the mean-state total neutral mass density output from the standard MET model. On output Metden is modified by the addition of a stochastic component, as described earlier in this report. The other parameters in the argument list are latin, $a_p$in and Iseed0. As described previously, if SETWAVE2 is called once only, Iseed0 will remain unchanged. The input parameters latin and $a_p$in must be available within the orbit generator program whenever Pickbins is false so that they can be properly input to GETWAVE2 (in that case WAVES2 calculates the bins internally using the latin and $a_p$in values). If Pickbins is true, so that the a_p bin is explicitly user-selected, $a_p$in is not used at all. We strongly emphasize that a latitude bin cannot be explicitly selected even if Pickbins is true, because latitude will always vary (and the latitude bins will too) around an orbit for which this simulator was designed (i.e., for inclinations grater than about 45^o).

Other parameters are passed to GETWAVE2 through a Common block (WAVE). This Common block must be included within the orbit generator program *exactly* as specified in GETWAVE2. The parameters in this Common block include the three logical constants Reset, Pickbins and Warnings. They have their values set in SETWAVE2 (as previously discussed).

The remaining parameters in the Common block are Dt, Tmax, Iseed and $a_p$bin. As already discussed, $a_p$bin may have been previously set in SETWAVE2. The time step, Dt, and the simulation time, Tmax, are set within the orbit generator program. If Reset is reset to true during the course of a simulation, the random number seed, Iseed, is reset by adding the integer 2 to its previous value. This method will ensure that Iseed remains large and odd while not interrupting program execution (as would occur if a new value of Iseed0 was required to be manually input from a terminal by the user).

A single simulation should not be allowed to exceed Tmax. If the elapsed time exceeds Tmax, Reset is reset to true, Elaptime is reset to zero, the random number seed (Iseed) is updated, and a new simulation (which may follow the previous one) is initiated. Similarly, a new simulation is initiated if Pickbins is false and the a_p value changes. If Tmax exceeds three hours and Pickbins is false, then it is likely that a_p will change because it is a three hour index. Therefore the simulations are not allowed to exceed three hours. If the user inputs a value of Tmax that is greater than three hours, the subroutine WAVES2 will reset that value to three hours and issue a warning (if Warnings is true).

Subroutine WAVES2

The subroutine WAVES2 is the heart of the simulator, and is called for every time step. Given either the user-specified or MET model inputs (through GETWAVE2), it selects the correct set of autoregression coefficients and then determines a complete set of stochastic wave amplitudes on a fixed fifteen second time grid. It keeps track of, and updates, the elapsed simulation time. If a variable time step is employed, it determines the corresponding position on the uniform time grid from which it determines the correct simulated wave amplitude. WAVES2 outputs a single dependent variable WAVE that is the wave amplitude expressed as a decimal.

Modifications Required in User-Supplied Orbit Generator Program

The four following parameters need to be set by the user directly before calling GETWAVES within the user-written orbit generator program:

a) Dt	(set once only if using a fixed time step)
b) latin	(set on every call)
c) $a_p$in	(set once only)
d) Tmax	(set once only)

The subroutines that need to be called from within the user-written orbit generator program and their calling sequence are

a) <u>Thermospheric density model</u> (e.g., MET)

then immediately call next routine **once only**

b) <u>SETWAVE2</u>

then immediately call next routine **multiple times**

c) <u>GETWAVE2</u>

Technical and Programmatic Problems

Any problems of either a technical or programmatic nature should be addressed to

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CONCLUSIONS

A stochastic wave generation model for simulating thermospheric gravity waves has been developed that is based on the characteristics of mean wave spectra calculated using standard Fast Fourier Transform (FFT) methods. The stochastic model was devised by fitting the maximum entropy spectrum for a second order autoregression model to the FFT spectrum in the frequency domain. The resulting model was found to characterize the overall frequency variation of the data.

The model has associated with it two input parameters. These parameters are latitude and the 3-hourly a_p index 6.7 hours prior to the time of interest. In either case the parameter input selects one of two possible bins for each index, so that the model has a total of four sets of defining parameters.

The model has certain restrictions concerning its use that are related to the data. These have been thoroughly explained in section II.1, and will not be repeated here.

Acknowledgments. I wish to extend my considerable gratitude to Mr. Wade Batts for creating ASCII data files for my use from the initial binary data supplied by NSSDC. I also wish to thank Drs. Robert E. Smith and B. Jeffrey Anderson for their support of this work, and Dr. Steve Smith for helpful conversations during the course of this work. I am grateful to the National Space Science Data Center (NSSDC) for supplying the satellite data, and I am particularly indebted to Mr. Ralph Post (NSSDC) for his prompt assistance with aspects of the data acquisition. I also thank the NATE experiment Principal Investigator Dr. Nelson Spencer and his co-investigators.

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APPENDIX A

PROGRAM LISTINGS

The following pages contain the program listings for the subroutines SETWAVE2, GETWAVE2, WAVES2 and GAUSSD and the function subprogram RAN1. The coding for this software is written in FORTRAN 77. It is not machine specific and should therefore be portable between different machines.

```
      SUBROUTINE SETWAVE2 (ISEED0)

      IMPLICIT      NONE
      INTEGER       APBIN, LATBIN, ISEED, ISEED0
      REAL          DT, TMAX
      CHARACTER*1   ANSWER
      LOGICAL       PICKBINS, WARNINGS, RESET

      COMMON / WAVE / DT, TMAX, ISEED, RESET, PICKBINS,
     >                APBIN, WARNINGS

C...Set option for explicitly selecting low or high ap bin for wave
C...simulator.
C...Two ap bins correspond to ap values below the 50th percentile (the
C...low ap bin for ap values less than or equal to 7) and those above the
C...50th percentile (the high ap bin for ap greater than 7). If the option
C...of explicitly selecting these bins is rejected, the bin is chosen
C...according to the values of 3-hourly ap that are input to the MET model.
      PRINT *,'Explicitly select ap bin for wave simulator?'
      PRINT *,'(Y/N)'
1     FORMAT (A1)
      READ 1, ANSWER
      IF (ANSWER.EQ.'Y'.OR.ANSWER.EQ.'y')  THEN
        PICKBINS = .TRUE.
        PRINT *,'Low (=1) or high (=2) ap bin?'
        READ *, APBIN
      ELSE
        PICKBINS = .FALSE.
      END IF

C...An initial seed for the random number generator used in the wave
C...simulator is required. For subsequent simulations the seed is
C...internally incremented by 2.
      PRINT *,'Set initial wave simulator seed (large odd integer)'
      READ *, ISEED0

C...Warnings will be typed from the wave simulator if certain parameters
C...are incorrectly specified. For an "expert" user these can be
C...suppressed by setting the warnings option to false.
      PRINT *,'Suppress warning or error messages? (Y/N)'
      READ 1, ANSWER
      IF (ANSWER.EQ.'Y'.OR.ANSWER.EQ.'y')  THEN
        WARNINGS = .FALSE.
      ELSE
        WARNINGS = .TRUE.
      END IF

C...End setup for wave simulator

      RETURN
      END
```

```
      SUBROUTINE GETWAVE2 (METDEN, LATIN, APIN, ISEED0, TOTDEN)
      IMPLICIT   NONE
      INTEGER    JSTEP, NRESET, ISEED, ISEED0, APBIN, LATBIN,
     >           OLDLATBIN
      REAL       METDEN, LATIN, APIN, TOTDEN, DT, TIMESTEP(720),
     >           ELAPTIME, TMAX, OLDAP, WAVE
      LOGICAL    RESET, PICKBINS, WARNINGS

      COMMON / WAVE / DT, TMAX, ISEED, RESET, PICKBINS,
     >                APBIN, WARNINGS

      IF (ELAPTIME.GT.TMAX .OR. (.NOT.RESET .AND..NOT.PICKBINS
     >     .AND. OLDAP.NE.APIN))  RESET = .TRUE.
      IF (ABS(LATIN).GT.40.0)  THEN
        LATBIN = 2
      ELSE
        LATBIN = 1
      END IF
      IF (LATBIN.NE.OLDLATBIN) RESET = .TRUE.

      IF (RESET)  THEN
        NRESET = NRESET+1
        ISEED  = ISEED0+2*NRESET       ! this keeps seed odd
        OLDAP  = APIN
        OLDLATBIN = LATBIN
        ELAPTIME = 0.0
      END IF

C...Note that WAVES is called every time
      CALL WAVES2 (APIN, LATIN, DT, TMAX, ISEED, RESET,
     >              PICKBINS, APBIN, WARNINGS, WAVE)
      ELAPTIME = ELAPTIME+DT
      TOTDEN   = (1.0+WAVE)*METDEN

      RETURN
      END
```

```
      SUBROUTINE WAVES2 (APIN, LATIN, DT, TMAX, ISEED, RESET,
     >                   PICKBINS, APBIN, WARNINGS, WAVE)

C...This subroutine/model is based on the analysis of AEC NATE data (see
C...accompanying report by Michael P. Hickey, 1995).
C...It is valid only for inclinations greater than about 45 degrees
C...and for approximately circular orbits between about 200 and 500 km
C...The time resolution of the original data and for this model is
C...15.0 seconds. The perturbations output by this subroutine are used
C...to modify the total mass density of the MET model and are intended
C...for simulations related to atmospheric drag effects (e.g., guidance,
C...navigation and control).

C...NPUTS:  APIN      is the same ap value that is input to MET model;
C...        LATIN     is latitude;
C...        DT        is the next time step, which must be at least
C...                  15 seconds (the time resolution of original data).
C...                  If the input value of DT is less than 15 s it is
C...                  automatically reset to 15.0;
C...        TMAX      is the maximum time duration (sec) of simulation.
C...                  It is advised that TMAX not exceed 3 hours (the
C...                  time resolution of the ap index);
C...        ISEED     is a large odd integer for random number generator;
C...        RESET     tells subroutine to go back to setup mode if it is
C...                  true. It should be reset when the ap  bins varies;
C...        PICKBINS  tells subroutine to override APIN inputs and
C...                  explicitly select required ap bin;
C...        APBIN     is the explicitly selected ap bin when PICKBINS is
C...                  true;
C...        WARNINGS  tells subroutine to type all warnings that occur
C...                  when either invalid input parameters are reset
C...                  internally or when WAVES2 should be recalled in
C...                  setup mode. If WARNINGS is false, no warnings are
C...                  typed to the screen, although the user should be
C...                  aware that internal resetting may be occuring if
C...                  the subroutine is being misused.

C...OUTPUT:  WAVE     is the wave percentage amplitude expressed as a
C...                  decimal. WAVE is a single dependant variable.
C...                  Subroutine WAVES2 is called every time step.

C...Additional Subroutines Employed: GAUSSD and RAN1 (random # generators)
```

```
      IMPLICIT      NONE
      INTEGER       ISEED, LATBIN, APBIN, N, K, I, IGRID, JGRID
      REAL          TMAX,
     >              APIN, LATIN, DT, A, A1, A2, WAVE, NOISE(721), PHI,
     >              STNDEV, RATIO, ELTIME, PHI1, PHI2,
     >              SCALE(2,2), AR2(8)
      LOGICAL       FIXDSTEP, SETUP, RESET, PICKBINS, WARNINGS;
     >              STOPFLAG
C...AE-C parameters:
      DATA          AR2    / 1.1792, -0.24832, 1.2764, -0.33955,
     >                       1.4367, -0.51164, 1.3461, -0.42737 /
      DATA          SCALE  / 1.385E-2, 2.093E-2, 1.171E-2, 2.440E-2 /
      DATA          SETUP     / .TRUE. /

      IF (RESET) SETUP = .TRUE.

C...Check that DT and TMAX are both nonzero. Type fatal error message
C...and terminate program execution if either one of them is zero.
      STOPFLAG = .FALSE.
      IF (DT.EQ.0.) THEN
        PRINT 1
        STOPFLAG = .TRUE.
      ELSE IF (TMAX.EQ.0.) THEN
        PRINT 2
        STOPFLAG = .TRUE.
      END IF
      IF (STOPFLAG) STOP

C...Further check that DT is no smaller than 15 sec and that TMAX is no
C...greater than 3 hrs. If they are, reset them to their nominal values.
      IF (DT.LT.15.0)  THEN
        DT = 15.0
        IF (WARNINGS) PRINT 3
      END IF
      IF (TMAX.GT.1.08E4)  THEN
        TMAX = 1.08E4
        IF (WARNINGS) PRINT 4
      END IF

C...Commence setting latitide & ap bins, white noise array on a constant
C...15-sec time grid.
      IF (SETUP)  THEN

        SETUP = .FALSE.
        RESET = .FALSE.

        N = 1+TMAX/15.0
C...Generate white noise of zero mean and unit standard deviation
        CALL GAUSSD (NOISE, N, ISEED)

C...PICKBINS = true will override the input value of ap.
        IF (.NOT.PICKBINS)  THEN
          IF (APIN.LE.7.0)  THEN
            APBIN = 1
          ELSE
            APBIN = 2
          END IF
        END IF
        IF (ABS(LATIN).LE.40.0)  THEN
```

```
          LATBIN = 1
          PHI1 = AR2 (2*APBIN-1)
          PHI2 = AR2 (2*APBIN)
        ELSE
          LATBIN = 2
          PHI1 = AR2 (4+2*APBIN-1)
          PHI2 = AR2 (4+2*APBIN)
        END IF
        STNDEV = SCALE (LATBIN,APBIN)
      END IF

C...Wave model is valid on a fixed 15 second grid, but any variable
C...time step can be input. We must therefore keep track of the total
C...elapsed time, and at each (possibly variable) step determine the
C...corresponding position on the fixed 15 second grid.
C...Note that IGRID is the position on the fixed 15-sec grid, while
C...JGRID is the projected position calculated from the elapsed time.
C...For first time:
      IF (ELTIME.EQ.0.0)  THEN
        IGRID = 1
        JGRID = 1
        A = NOISE(1)
C...and for all subsequent times:
      ELSE
        JGRID = 1+INT(ELTIME/15.0)
        DO WHILE (IGRID.LT.JGRID)
          IGRID = IGRID+1
          A = PHI1*A1 + PHI2*A2 + NOISE(IGRID)
        END DO
      END IF
      A2 = A1
      A1 = A

C  Now make variance fit data by increasing standard deviation from
C  unity to STNDEV.
      WAVE = STNDEV*A

      IF (ELTIME.GT.TMAX)  THEN
        PRINT 5
        WAVE = 0.0
      END IF
      ELTIME = ELTIME+DT

1     FORMAT(' FATAL ERROR: DT is zero in WAVES2')
2     FORMAT(' FATAL ERROR: TMAX is zero in WAVES2')
3     FORMAT(' WARNING: DT has been increased to 15 seconds')
4     FORMAT(' WARNING: TMAX has been decreased to 3 hours')
5     FORMAT(' WARNING: Elapsed time > TMAX. WAVE now set to 0.0',/,
    >        '              Recall WAVES2 in setup mode')

      RETURN
      END
```

```
      SUBROUTINE GAUSSD (X, N, ix)
C     routine to produce vector of gaussian distributed random numbers
C     in X(n).  The series in X(n) will have approximate zero mean and
C     standard deviation of 1.0.  Polar Method algorithm taken from
C     p. 104, Seminumerical Algorithms,
C     vol 2 of The Art of Computer Programming by D. E. Knuth, 1969.
C
C     ix is random number seed, i.e., large odd integer.
C
      implicit none
      integer i, ix, iy, n
      REAL X(N), RAN1
      real s, v1, v2


     I = 0
      iy = ix

      do while (i .lt. n)

         V1 = 2.0*ran1(iy) - 1.0
         V2 = 2.0*ran1(iy) - 1.0

         S = V1*V1 + V2*V2

          if (s .lt. 1.0) then

              S = SQRT(-2.0*ALOG(S) / S)

              I = I + 1
              X(I) = V1 * S
              I = I + 1
              if (i .le. n) then
                  X(I) = V2 * S
              end if

          end if

      end do

      ix = iy
     RETURN

     END
```

```
      FUNCTION RAN1 (IDUM)
C  Returns a uniform random deviate between 0.0 and 1.0. Set IDUM to any
C  negative value to initialize or reinitialize the sequence.
C  Copied from Numerical Recipes, W.H. Press, B.P. Flannery,
C  S.A. Teukolsky & W.T. Vetterling, Cambridge Univ. Press, 1986, p.196
      IMPLICIT   NONE
      INTEGER    IFF, IX1, IX2, IX3, J, M1, M2, M3, IA1, IA2, IA3,
     >           IC1, IC2, IC3, IDUM
      REAL       RM1, RM2, R, RAN1
      DIMENSION  R(97)
      PARAMETER  (M1=259200, IA1=7141, IC1=54773, RM1=1./M1)
      PARAMETER  (M2=134456, IA2=8121, IC2=28411, RM2=1./M2)
      PARAMETER  (M3=243000, IA3=4561, IC3=51349)
      DATA  IFF  /0/  ! as above, initialize on first call even if
                      ! IDUM is not negative
      IF (IDUM.LT.0 .OR. IFF.EQ.0)  THEN
         IFF=1
         IX1=MOD(IC1-IDUM,M1)          ! Seed the first routine,
         IX1=MOD(IA1*IX1+IC1,M1)
         IX2=MOD(IX1,M2)               ! and use it to seed the second
         IX1=MOD(IA1*IX1+IC1,M1)
         IX3=MOD(IX1,M3)               ! and third routines.
         DO  J = 1, 97                 ! Fill the table with sequential
            IX1=MOD(IA1*IX1+IC1,M1)    ! uniform deviates generated by
            IX2=MOD(IA2*IX2+IC2,M2)    ! the first two routines
            R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1      ! Low and high-
         END DO                        ! order pieces combined here.
         IDUM=1
      END IF
      IX1=MOD(IA1*IX1+IC1,M1) ! Except when initializing, this is
      IX2=MOD(IA2*IX2+IC2,M2) ! where we start. Generate the next
      IX3=MOD(IA3*IX3+IC3,M3) ! number for each sequence.
      J=1+(97*IX3)/M3         ! Use the third sequence to get an
                              ! integer between 1 and 97
      IF(J.GT.97 .OR. J.LT.1) PAUSE
      RAN1=R(J)               ! return that table entry,
      R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1     ! and refill it.
      RETURN
      END
```

APPROVAL

AN ENGINEERING MODEL FOR THE SIMULATION OF SMALL-SCALE THERMOSPHERIC DENSITY VARIATIONS FOR ORBITAL INCLINATIONS GREATER THAN 40 DEGREES

Michael P. Hickey

The Information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classifications Officer. This report, in its entirety, has been determined to be unclassified.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1996	Contractor Report

4. TITLE AND SUBTITLE
An Engineering Model for the Simulation of Small-Scale Thermospheric Density Variations for Orbital Inclinations Greater Than 40 Degrees

5. FUNDING NUMBERS
NAS8–38333

6. AUTHORS
M.P. Hickey

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Physitron, Inc.
3304 Westmill Drive
Huntsville, Alabama 35805

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR–201140

11. SUPPLEMENTARY NOTES
Prepared for Systems Analysis and Integration Laboratory, Science and Engineering Directorate
Technical Monitor: Dr. B. Jeffrey Anderson

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—U.S. Government Agencies and U.S. Government Agency Contractors Only
Subject Category 18

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes the development of an engineering model that simulates small-scale density variations in the thermosphere and provides engineers with a set of instructions enabling them to implement the model in their existing orbital propagation models. The model is provided as a callable subroutine that can be easily used in conjunction with the MET model, and is simplistic enough to contain the essential elements of the variations without overburdening computational resources. The model FORTRAN code is included at the end of this report.

The model is derived from the spectral analysis of thermospheric neutral density data obtained from the Neutral Atmosphere Temperature Experiment (NATE) on the Atmosphere Explorer-C satellite between December 1974 and December 1978. During this time, the 68.1° inclination orbits were approximately circular between 220 and 400 km altitude. Solar activity was low to moderate during this period.

Total densities for contiguous strings of 15 sec density data values were spectrally analyzed, and Fast Fourier Transform periodograms were computed for each string. The periodograms were binned according to latitude and the geomagnetic activity index a_p, and then average periodograms were computed for each bin. Finally, stochastic (autoregression) models were fit to each of the average periodograms. Two laditude bins and two a_p bins were employed.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
thermosphere, thermospheric density, waves, density variations simulation, GN&C design	48	NTIS

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

National Aeronautics and
Space Administration
Code JTT
Washington, DC
20546–0001